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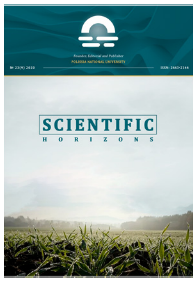

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Technological Aspects of Energy-Efficient High-Quality Cleaning of Indoor Air from Harmful Impurities

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Abstract. Bringing to safe health standards and maintaining the basic parameters of the air (microclimate) in the premises for various purposes within the established limits with a high level of efficiency, pro-vides an opportunity to solve the problem of national importance – public health and the necessary environmental characteristics. The purpose of the study is to develop technology and foundations for the construction of universal systems of automated high-quality air purification in rooms for various purposes. Methods of analysis, synthesis, mathematical modelling, and engineering calculations were used in the research process. The technology, composition, and structure of universal systems for au-tomated cleaning and maintenance of the required indoor air quality, which provides automatic control of air parameters, have been developed. The composition and features of software and hardware are substantiated, the method of engineering calculation, structure of air purification system is developed and its technical parameters are defined. The synergetic effects in the implementation of air purification, which are achieved through a comprehensive, consistent with the procedures and pro-cesses of sequential parallel processing of injected and filtered air, have been investigated and proved. Developed technology and systems provide the ability to purify large volumes of air at high speed and quality in rooms with different levels of mechanical contamination, microflora, other harmful impurities, including microorganisms, allergens, dangerous viruses that cause infections with pathogens diseases characterised by mass and high rate of spread, such as COVID-19. For the first time, the problem of creation of energy-efficient high power systems of complex air purification for industrial premises of large sizes, which are 2.5-4 times more effective on all basic indicators in com-parison with the best analogues has been solved

Keywords: air purification system, ultraviolet, ozone, disinfection, microclimate

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INTRODUCTION

The recommended parameters of the microclimate of livestock premises are regulated by departmental norms of technological design for each type of premises and animal species [1-4]. The main parameters of the air environment of livestock premises are: temperature, relative humidity, speed and pollution of air by harmful impurities. Components of biological or chemical pollution of the air environment of animal housing, such as: ammonia, carbon dioxide, hydrogen sulphide, methane, biological impurities (viruses, bacteria, fungi, mould, etc.), dust and other mechanical impurities [1-4], in case of exceeding the maximum permissible concentration (MPC) lead to a decrease in productivity, increased animal morbidity or death of livestock.

To ensure the recommended parameters of the air environment of agricultural buildings and structures, active ventilation is used, air exchange is recommended to be installed depending on the live weight of the animals in the room [1-4]. In particular, the minimum permissible air exchange for pigs in the warm period of the year is 60 m^3/h per 1 quintal of live weight, in the heating period – 30 m^3/h, respectively, the minimum air exchange of a pig farm per 1 thousand animal units is 30-60 thousand m^3/year. A significant amount of electricity is used to drive the fans, at the same time, together with the air, a significant amount of harmful substances enters the environment, energy costs increase to maintain the temperature in the room [4; 5]. The development and application of energy-efficient technology for cleaning and disinfecting the air of livestock premises from harmful impurities of chemical and biological origin would ensure the specified parameters of the microclimate, save a significant amount of thermal energy for heating in the cold season, and reduce the anthropogenic load on the environment [5].

An effective technical solution for cleaning and disinfecting the air of livestock premises from harmful chemical and biological impurities is the use of open [6-13] and closed [9; 14; 15] bactericidal installations based on low-pressure ultraviolet lamps [5; 16-22]. Such installations are widely used in medical and preventive treatment facilities (hospitals, clinics, sanatoriums, etc.), civilian premises with large crowds (children's educational institutions, commercial and office premises, offices, etc.), for disinfection of food, water, etc. The disinfecting effect of ultraviolet bactericidal lamps is photochemical damage to the DNA of the microorganism when using irradiation of the ultraviolet range with a peak wavelength of 265 nm, which leads to cell death, and in the bactericidal and disinfecting action of the disinfectant [20; 22; 23]. The dependence of bactericidal efficiency of ultraviolet radiation on the wavelength is called the spectrum of action [20]. Bacteria and viruses (rods, cocci) are more sensitive to the disinfecting effect of ultraviolet radiation, protozoa and fungi are less sensitive, and spore forms of bacteria are the most resistant. The use of irradiators of the ultraviolet range in closed recirculators provides air disinfection from pathogenic microflora up to 99.9% [6; 7; 20; 22].

The use of bactericidal devices for purification and disinfection of air is possible in the form of irradiators (open bactericidal units), recirculators (closed bactericidal units) or purification modules in supply and exhaust units of general exchange ventilation [17]. The main difference between recirculators and irradiators is that irradiators neutralise pathogenic microflora both in the air of the working area and on surfaces, but cannot be used in the presence of humans and animals due to the risk of skin and mucous membrane burns. Ultraviolet bactericidal recirculators decontaminate the air flow in an isolated channel or chamber; can be used in constant operation in the presence of humans and animals, because the flow of UV-c radiation does not enter the working area of the room.

If ultraviolet radiation of the bactericidal spectrum neutralises pathogenic microflora and chemical compounds only in the irradiation zone, then ozone is able to oxidise harmful impurities both in the recirculator channel and in the working area of the room. At the same time, ozone is a chemical of the highest class of danger, because its maximum concentration limit for humans is 0.1-0.2 mg/m^3, and therefore there is a need to develop and apply ACS parameters of the air purification system and air parameters in the working area.

The purpose of the study is to establish the technical and technological parameters of the auto-matic energy-efficient system for purifying the air of livestock premises from harmful impurities to achieve maximum energy efficiency of their use.

MATERIALS AND METHODS

To determine the initial technical, technological, and design parameters of the recirculator for cleaning the air of livestock premises from harmful impurities, the study considers modern effective bactericidal technical means of irradiation of air and surfaces, industrial ozone generators and technological requirements for their use in agricultural premises. Substantiation of technical parameters of air purifiers is carried out taking into account the requirements for microclimate parameters and modern research and trends in this field. Using the conducted analytical and laboratory investigations, the technological schemes of the automated bactericidal system of a recirculator for creation of an energy-efficient microclimate of livestock premises are developed. The method of engineering calculation is based on the establishment of the power of bactericidal radiation to achieve a given value of bactericidal efficiency. The dynamics of the concentration of harmful substances in the working area of the livestock premises during irradiation with ultraviolet waves was studied in laboratory and industrial conditions, and a decrease in the concentration of harmful impurities from the intensity and time of air treatment was found. The concentration of harmful impurities in the laboratory chamber and the working area of the livestock premises was recorded by Dozor-SP and Dozor-SM gas analysers, ozone concentration – 01-02.P-P cheluminescent ozone analyser, tempera-ture and relative humidity – Testo 608H1 thermohygrometer.

To develop an algorithm for controlling the modes of operation of energy efficient equipment to create a microclimate of livestock facilities, analytical studies of modern technical means for control and management of microclimate parameters of livestock facilities were carried out taking into ac-count the recommended air parameters and devices for monitoring temperature, humidity, physical and chemical composition of air. When substantiating the system of energy-efficient equipment for creating a microclimate of livestock premises, a set of technical means for creating a microclimate is taken as a basis: supply and exhaust unit with heat recovery and closed and open bactericidal units for air purification from harmful impurities. The algorithm takes into account the permissible limits of the parameters of the air environment of the working area and the mechanisms of their control: ozone (up to 1 mg/m^3), ammonia (up to 20 mg/m^3), hydrogen sulphide (up to 10 mg/m^3), carbon dioxide (up to 0.3%), and temperature and relative humidity in accordance with departmental standards of technological design. The basic electrical scheme was developed and an experimental sample of the control system of energy-efficient equipment for creating the microclimate of livestock premises was manufactured using the developed algorithm. The scheme provides control of the recommended parameters of the air environment, control of the summer ventilation system, supply and exhaust units with heat recovery of exhaust air, devices for air purification from harmful impurities, and the indication signalling the operation of the microclimate system. CZMCU-131 MQ131 sensors with sensitivity from 0 to 0.5 ppm were used for ozone monitoring in the working area of the room.

RESULTS AND DISCUSSION

To clean and disinfect the air of livestock premises from harmful impurities of chemical and biological origin, it is proposed to use an air purification system consisting of an air treatment duct, an ozoniser, low-pressure ultraviolet bactericidal lamps, which are installed in the air flow blown by a fan (recirculator), automatic control system (ACS) parameters of the cleaning system and equipment to create a microclimate of the room (Fig. 1).

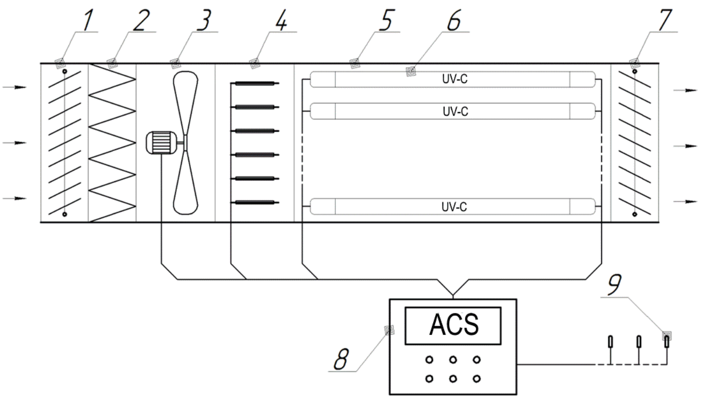

Figure 1. *Energy efficient system for cleaning the air environment of livestock premises from harmful impurities*
Notes*: 1 – intake protective grid (blinds); 2 – filter; 3 – fan; 4 – ozoniser; 5 – irradiation chamber; 6 – UVB lamps; 7 –exhaust protective grid (blinds))*

Fans inject the flow of air entering the recirculator through the ventilation grilles, ozone is generated from the oxygen contained in the air, then the air flow is treated simultaneously with ozone and irradiated with bactericidal lamps, disinfected and released. The recirculator housing forms an efficient irradiation chamber, as the inner surface of the recirculator is made of reflective material (polished metal, stainless steel, aluminium, etc.).

If the recirculation air flow in the irradiation chamber is significantly exceeded or if the irradiator power is reduced, the volumetric bactericidal dose will decrease, and the bactericidal efficiency of the recirculator as a whole will decrease accordingly. Therefore, to achieve the specified value of bactericidal efficiency of bactericidal air recirculators, it is first necessary to agree on the power of bactericidal radiation and air productivity of fans. Bactericidal radiation power Φ_{bc}, W to achieve a given level of bactericidal efficiency J_{bc}, % can be determined by the equation [17; 20; 24; 25]:

$$\Phi_{bc} = \frac{-V_{air} \cdot \ln{(1 - J_{bc} \cdot 10^{-2})}}{3600 \cdot k_f \cdot k_r \cdot k_d \cdot \sigma_v} \quad (1)$$

where Φ_{bc} – bactericidal power of UVB lamps, W; V_{air} – volume of air treated in the recirculator chamber, m^3; k_f – UFB flow utilisation factor. In the case of the location of lamps in the air flow – k_f=0.4-0.5, if not in the flow – k_f=0.7-0.8; k_r – coefficient of multiple reflections of UVB flow from the inner walls of the recirculator chamber, k_r=1.2-1.5; k_d – decay coefficient of bactericidal flux by the end of lamp life, k_d=0.7-0.8; σ_v – microorganism photosensitivity constant. Rational values of bactericidal efficiency of UV-c radiation Jbc for industrial premises are in the range of 80-95% [26]. With a further increase in the set value of bactericidal efficiency Jbc, it is necessary to significantly increase the installed power of the emitters. Therefore, the rational values of the specific power of bactericidal radiation is in the range Φ_{bc}=65-121 W/thsd. m^3 of air.

If pathogenic microflora or chemical impurities are present in the air of the work area, which are ineffectively neutralised by UV-c radiation, they can be destroyed or inactivated by ozone during ultraviolet irradiation (photooxidation). Ozone is generated from oxygen contained in atmospheric air under the action of ultraviolet radiation with a wavelength of 185 nm (during the operation of ultraviolet lamps). This method of ozone generation depends on the power of ultraviolet lamps, control of its concentration in the chamber and the working area of the room can be done only by exposure to radiation, as a result of which the lamps fail prematurely. In addition, given the instability of ozone, the concentration of which depends on the oxygen concentration at the recirculator intake, temperature and humidity, the presence and concentration of oxidising substances, it is more appropriate to use ozone-free UV-c lamps and ozonisers with control of ozone concentration in the working area of the room.

The productivity of the ozone generator QOZ, mg/h can be determined by the equation:

$$Q_{oz} = k_{air} \cdot k_d \cdot V_{ro} \cdot C_{oz} \quad (2)$$

where k_{air} – multiplicity of air exchange of the room, h^{-1}; k_d – ozone decomposition factor; V_{ro} – volume of the room, m^3; C_{OZ} – set concentration of ozone in the room, mg/m^3.

The maximum concentration limit of ozone in the working area of the room during the presence of people is 0.1 mg/m^3. Therefore, the minimum specific productivity of the ozoniser in this case (excluding the coefficient of ozone decomposition) in the presence of people in the room is Q_{OZspec}=0.1 mg/hour·m^3.

When cleaning the air from harmful impurities and pathogenic microflora using a cleaning system based on a type RPB 1.0-6/30 recirculator (Fig. 2), the air exchange of the room can be reduced without violating the specific parameters of the air. The most significant energy savings to maintain the specific air temperature will be when maintaining the concentrations of harmful impurities at the level of their MPC.

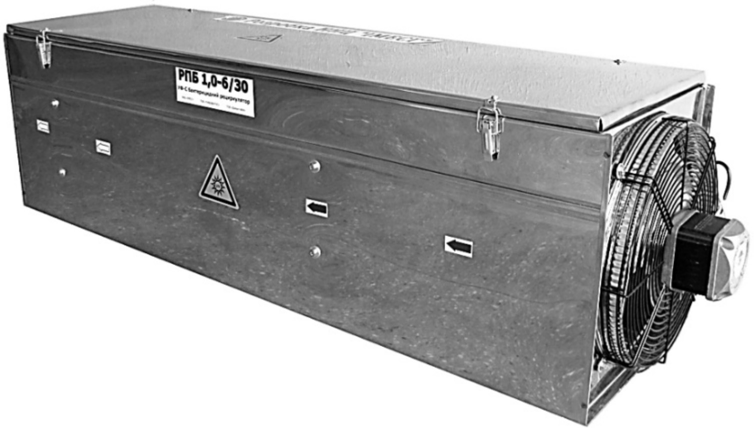

Figure 2. *Experimental-industrial sample of RPB 1.0 UFB air recirculator (NSC "IMESG" – LLC Turboventus)*

Possible modes of bactericidal recirculator operation: manual (switched on by service personnel for preventive purposes), cyclic (with setting of operating time and downtime) and automatic (automatic air quality control is carried out). For effective cleaning of the air of the working area of the room, it is advisable to use recirculators in a cyclic or fully automatic mode with the use of air quality sensors. The advantage of the cyclic mode of operation of recirculators is a simple control scheme and long operation of UVB low pressure lamps, which has a positive effect on their service life, the disadvantage is the lack of control over air pollution, ozone concentration in the working area, and cyclic cleaning.

In automatic mode, it is advisable to control the air parameters in the working area of the room, turn off the recirculator when the ozone level reaches the MPC value for humans or animals, and when the MPC of harmful substances after air treatment to turn on general ventilation. Thus, it is possible to ensure maximum efficiency of air purification and disinfection and minimum loss of thermal energy with ventilation air during the heating period. In summer, the ventilation of the room can work normally without considering the recirculator operation.

According to the defined modes of operation of the energy-efficient system of microclimate of livestock premises to create an automatic control system, the algorithm should consist of blocks of initial parameters: temperature and humidity in the room, maximum concentration of ozone and harmful substances in the working area, and units comparing these parameters with values and decision blocks (Fig. 3).

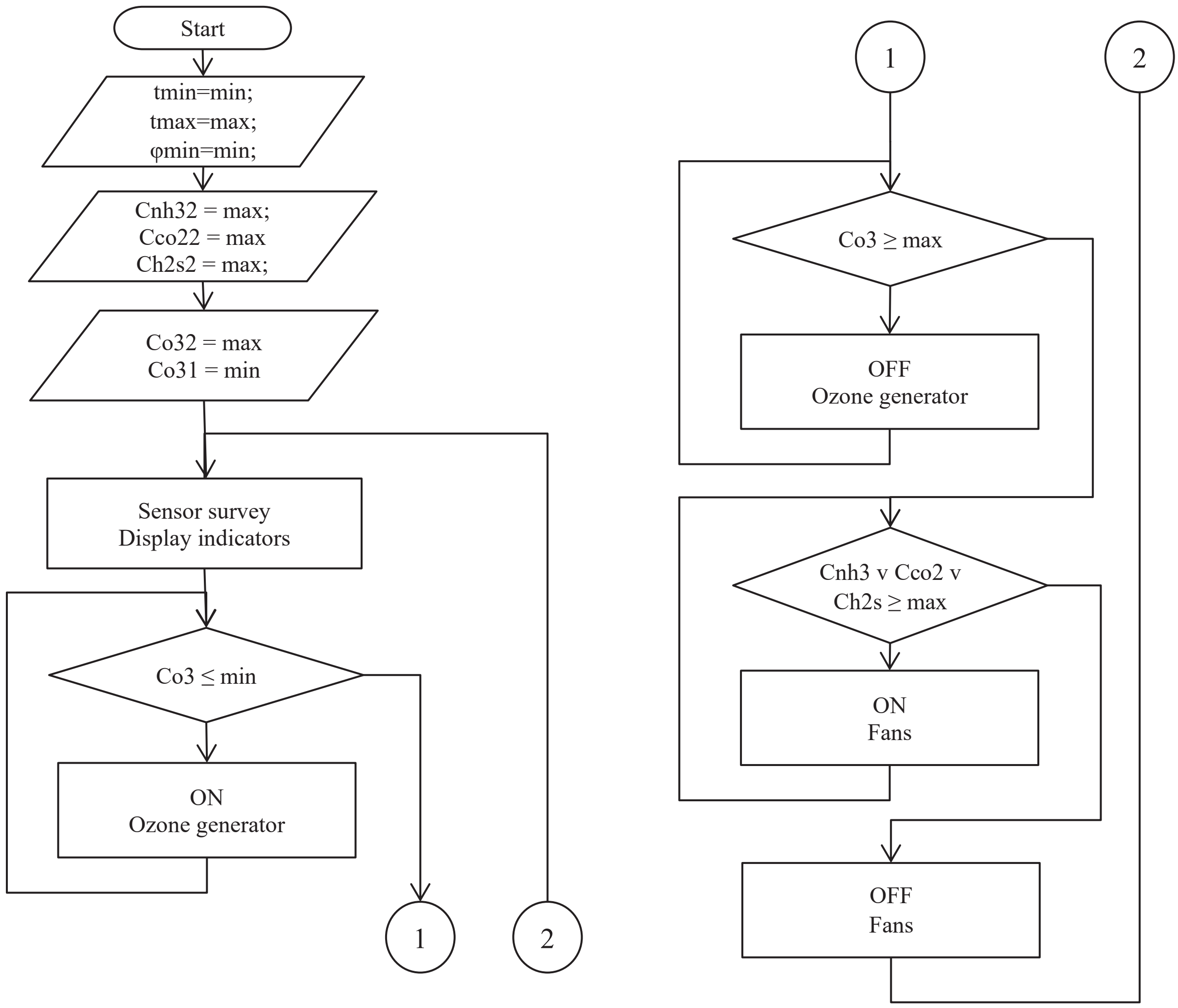

Figure 3. *Algorithm for controlling the system of energy efficient equipment to create an energy efficient microclimate of livestock facilities*

The algorithm works as follows: the minimum and maximum values of temperature and humidity in the room are set by the programme method or using controls according to the accepted technology and animal species, MPC of harmful substances in the air (ammonia, hydrogen sulphide, car-bon dioxide, methane, etc.). If the actual value of any harmful substance in the air of the working area is exceeded, the ozone generator is turned on until the ozone maximum concentration limit is reached. When the maximum concentration limit is reached, the generator is switched off. At the same time if the MPC of any harmful impurity is above permissible value – volumes of the general exchange ventilation of the room are switched on or increased.

To control the energy-efficient microclimate system, according to the developed algorithm (Fig. 3), an experimental sample of the automatic control system (ACS) of the energy-efficient microclimate of livestock premises with the use of air purification system was developed and manufactured (Fig. 4).

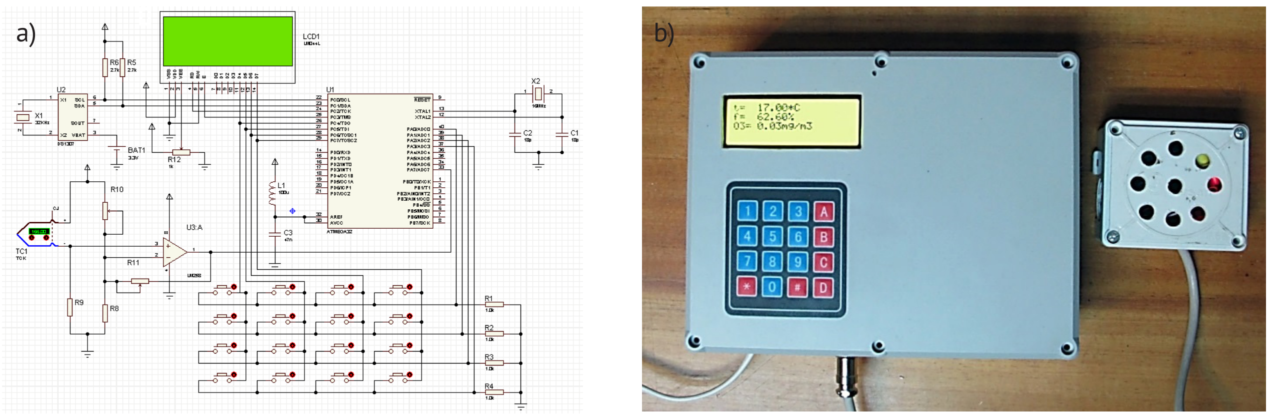

Figure 4. *Schematic electrical diagram (a) and appearance (b) of the experimental ACS unit for the microclimate parameters of livestock premises using an air cleaning system*

The ACS consists of a control and monitoring unit, and a remote sensor unit, provides control of temperature, relative humidity and ozone, and control of general ventilation units. The developed ACS unit provides monitoring of the concentration of ozone and harmful impurities in the air of the working area, automatic control of ozone concentration and general ventilation of the room to minimise energy costs and ensure normalised microclimate performance.

During the test of the RPB 1.0-6/30 bactericidal recirculator with ultraviolet lamps (total power of 180 W) and an ozoniser (capacity of 10 g/h) in a rabbit farm for 120 rabbits with a volume of 380 m^3, it was found that with the air exchange of 1.5-2.0 thsd. m^3/h, ACS provides the ozone concentration in the working area in the range of 0.02-0.2 mg/m^3, with an average value of ozone concentration of 0.15 mg/m^3, and the concentration of ammonia in the working area of the premises during production tests decreased from 14 mg/m^3 to 6 mg/m^3 (Fig. 5).

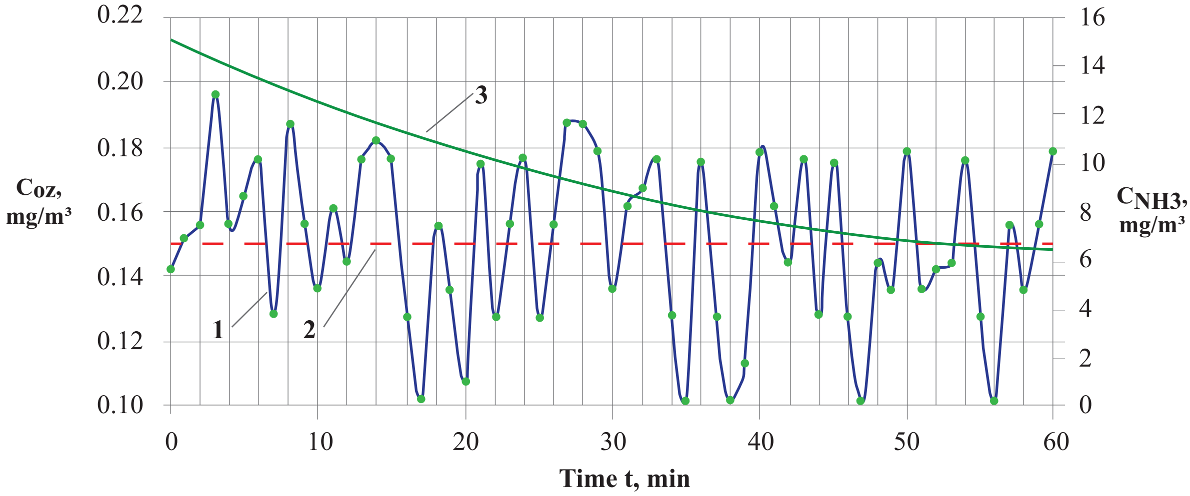

Figure 5. *Dynamics of ozone and ammonia concentration in the rabbit farm when using an energy-efficient system for cleaning the air environment of livestock premises*

Note*: 1 – ozone concentration in the working area of the room; 2 – average value of the concentration of ozone in the room during the test period; 3 – concentration of ammonia in the working area of the room*

CONCLUSIONS

The following conclusions were obtained from the study results:

1. To ensure maximum efficiency of cleaning and disinfection of indoor air from harmful impurities, it is advisable to use ozonisation and ultraviolet radiation in a closed chamber of the recirculator with an automatic control system of air parameters in the working area of the room.

2. When cleaning the air from harmful impurities and pathogenic microflora using the proposed automatic system based on a recirculator, the air exchange of the room can be reduced without violating the specific parameters of the microclimate.

3. Rational values of bactericidal efficiency of UV-c radiation J_{bc}=80-95%, specific power of bactericidal radiation Φ_{bc}=65-121 W/thsd. m^3 of air, the minimum specific productivity of the ozoniser Q_{OZspec}=0.1 mg/h·m^3.

The innovative technology developed in the article and the implemented SOPs are practically significant for the national economy as a whole and specifically for various industries. Their practical use helps to preserve human health, increase productivity in livestock and poultry, and curb the spread of various diseases, especially infectious diseases, including COVID-19. The equipment of all premises where there is a considerable quantity of people for preservation of their health and all premises for animals is perspective.

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Технологічні аспекти енергоефективного високоякісного очищення повітряного середовища приміщень від шкідливих домішок

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Анотація. Приведення до безпечних для здоров'я норм та підтримки у встановлених межах основних параметрів повітряного середовища (мікроклімату) в приміщеннях різного призначення із забезпеченням високого рівня економічності та енергоефективності, надає можливість вирішення проблеми державного значення – збереження громадського здоров'я та необхідних екологічних характеристик оточуючого середовища. Метою роботи є розроблення технології і основ побудови універсальних систем автоматизованого високоякісного очищення повітря в приміщеннях різного призначення. У процесі досліджень використано методи аналізу, синтезу, математичного моделювання та інженерних розрахунків. Розроблено технологію, склад і структуру універсальних систем для автоматизованого очищення та підтримки необхідної якості повітря в приміщеннях, яка забезпечує автоматичний контроль параметрів повітряного середовища і управління засобами очищення та підтримки необхідної якості повітря. Обґрунтовано склад і особливості програмного та апаратного забезпечення, розроблено метод інженерного розрахунку, структуру системи очищення повітря та визначені її технічні параметри. Досліджено та доведено синергетичні ефекти при здійсненні очищення повітря, які досягаються за рахунок комплексної, узгодженої за процедурами та процесами послідовно-паралельної обробки повітря, що нагнітається та фільтрується. Розроблені технологія і системи забезпечують можливість очищувати великі об'єми повітря з високою швидкістю та якістю в приміщеннях з різними рівнями його забрудненості механічними домішками, мікрофлорою, зокрема патогенною, іншими шкідливими домішками, включно з мікроорганізмами, алергенами, небезпечними вірусами, які приводять до інфікувань збудниками захворювань, що характеризуються масовістю та високою швидкістю поширення, наприклад COVID-19. Вперше вирішено проблему створення енергоефективних систем комплексного очищення повітря великої потужності для виробничих приміщень великих розмірів, які в 2,5–4 рази більш ефективні за всіма основними показниками у порівнянні з найкращими аналогами

Ключові слова: система очищення повітря, ультрафіолет, озон, знезараження, мікроклімат